THE COOPERATION OF RUSSIAN AND GERMAN METAL FORMING SCIENTIFIC SCHOOLS TO DEVELOP THE NEW ENERGY-EFFICIENT MATERIALS AND TECHNOLOGIES

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Abstract

The future scientific orientation of Katedra PDSS is in the area of materials forming and materials development with a focus on efficient processes regarding the use of energy and resources. Current research in the department PDSS is based on fundamental works on thermo-mechanical treatment of metals and on the modeling of nano-materials, rolled material and medical materials. This includes research on the relevant microstructural and macroscopic effects on the materials behavior. Together with its international research partners PDSS has excellent foundations for experimental research as well.

With its international focus and its educational programs for students and skilled employees PDSS is an important partner of the Russian metal processing industry which supports Russian companies to compete on a world-class level.

1. Introduction

Research on metal forming within the Katedra PDSS is characterized by its integrated approach on producing materials with demand meeting properties throughout the whole production process. This regards the geometry as well as the materials strength and surface characteristics. Going back to Professor P.I. Poluhin who initiated this kind of research approach practiced at NITU MISIS PDSS is still up to date.

Beginning in the 1970s research began to analyze the microstructure development during forming processes in order to influence the mechanical properties in the finished products. One important factor in this regard was micro-alloying of the materials. Later results of this research were the groundwork for thermo-mechanical treatment as an industrial process. Examples are the standards for thermo-mechanical treatment of metamorphic steel and the definition of temperature-time-conditioning in forming processes and the austenization before the γ/α-transformation.

While the mechanical characteristics of a material are directly dependent on the thermo-mechanical treatment surface characteristics and product geometry in respect of deviations in form, strength and residual stress are influenced by the process itself. For example, flatness and waviness of rolled products frequently originate from a locally and temporarily instable temperature field. The knowledge build over the years were published in many journal articles and books written by researchers of PDSS [1-4].

The scientific perspectives of PDSS also influenced the educational programs of NITU MISIS. Today, students of material science have broad knowledge on the influence of forming processes on materials characteristics, especially on different forms of thermo-mechanical treatment.

Bringing together knowledge from metallurgical science and material processing science creates huge potential for future development of new products and of new materials with high energy and resource efficiency. Therefore, creating new materials with application-specific characteristics will stay the central goal of research within Katedra PDSS.

Strengthening the development of new materials and processes by cooperation with partners

Research

Research of Katedra PDSS spans all fields of modern materials processing science with metallic materials as its main emphasis. Grounded in a long tradition but also following the demands of future industrial research the department is subdivided into four interacting groups which cooperate closely with each other (**Figure 1** shows the new structure of PDSS).

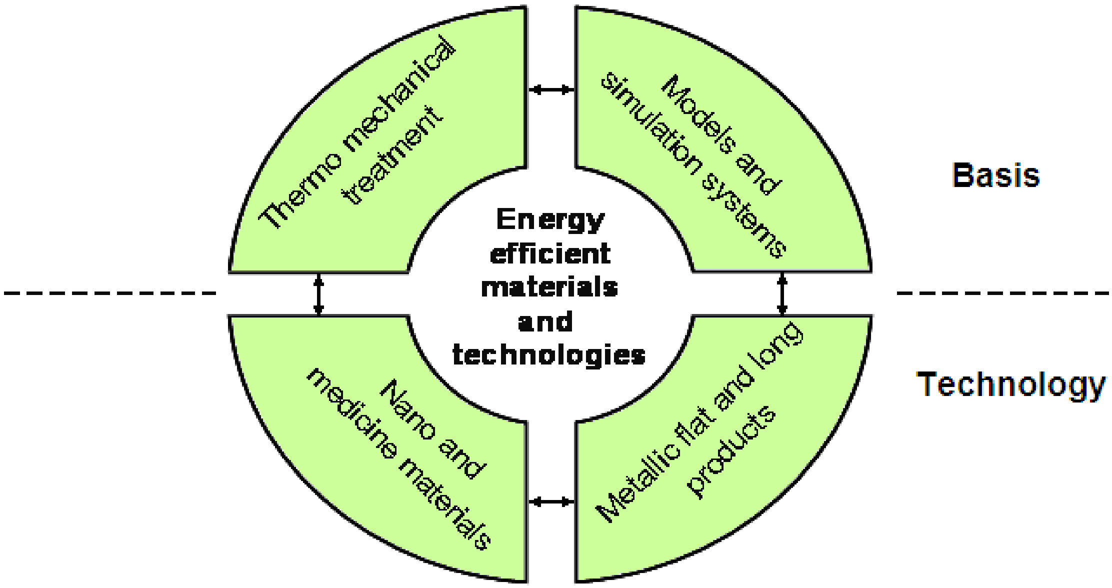

Fig. 1: Function area of department PDSS

Research on new energy-efficient materials and technologies represents the central objective of PDSS. This is supported by researchers focusing on thermo-mechanical treatment processes and on numerical simulation. On the technological side there are the fields of nano-materials and of medical materials development. Though, at first side the latter do not seem to be closely connected to the first named groups, there is a close interaction. Processes of phase transformation and microstructure development and their influence on physical characteristics are examples for interrelations which connect the different topics of research.

As the final properties of a newly developed material are dependent on the conditions of the production process each group makes its specific contribution towards the central objective of PDSS. There is a need for a holistic approach on materials science which integrates all steps of the production process from the microstructure after solidification to the semi-finished product with its final characteristics which must be suited to its purposed function.

The research group on thermo-mechanical treatment provides insights into the process conditions in hot and cold forming with heat treatment respectively. This includes:

- temperature time diagrams,
- strain hardening and softening,
- phase transformations,
- microstructure development in dependence of the process conditions in heating and cooling.

The group responsible for process modeling and simulation is concerned with the description of numerical models which explain the transformation processes and the property changes during forming processes. Explaining the materials flow on a macro level as well as on a micro level is of special relevance for describing the processes. Also, the buildup of residual stress during the production process is examined in order to be able to appropriately describe the whole production cycle. An example for this procedure is described in the article of [5].

Both research groups, nano-materials and medical materials, fall back to the findings of the aforementioned groups of thermo-mechanical treatment and numerical simulation and use them to create materials with specified new properties suited to their respective fields of application. This includes the needed form, size and surface quality of the finished product as well as process parameters as the required forming forces and thermal conditions which are also of importance regarding the energy efficiency of the production process. Another important field of interconnection between the groups is the analysis of tribological conditions and their effect on surface development. The goal of both groups is to develop new materials with properties tailored especially to their respective utilization.

With the technologies developed within PDSS many of the required characteristics which the new materials should reveal can be generated or influenced (see **Figure 2**). To broaden the research possibilities even more and to meet the complexity requirements of modern material development, PDSS also its cooperation with other research groups worldwide. First to name, PDSS closely cooperates with partners from within NITU MISIS, with the Institute for Metal Forming of TU Bergakademie Freiberg and with several research partners from Russia. Thus, researchers of PDSS are able to use the experimental facilities of the partners, offering additional possibilities for research on new materials and process technologies.

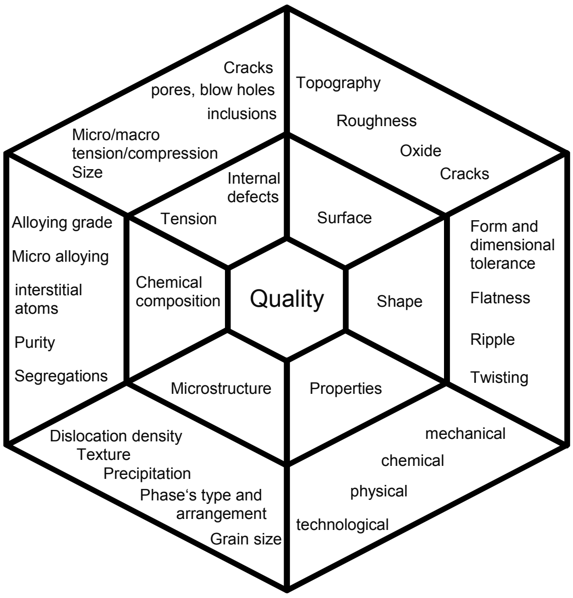

Fig. 2: Quality characteristics of products

In context with the general modernization of many research facilities of NITU MISIS several new experimental systems will be set up at Katedra PDSS. Amongst others, this includes:

- a deformation dilatometer for the temperature range between -150 °C to 1400 °C (**Figure 3**),
- an universal rolling mill for hot and cold rolling of long and flat rolled products and (**Figure 4**),
- facilities for heat treatment.

These investments are accompanied by the buildup of a metallographic laboratory with a focus on light microscopy. Together with the existing facilities for electron microscopy and mechanical testing and with the newly installed GLEEBLE 3500 system PDSS offers excellent possibilities for developing and testing all kinds of material processing technologies from solidification, hot and cold forming to heat treatment (see **Figure 5**).

Fig. 33: Quenching- and deformation dilatometer (BÄHR-Thermoanalyse GmbH)

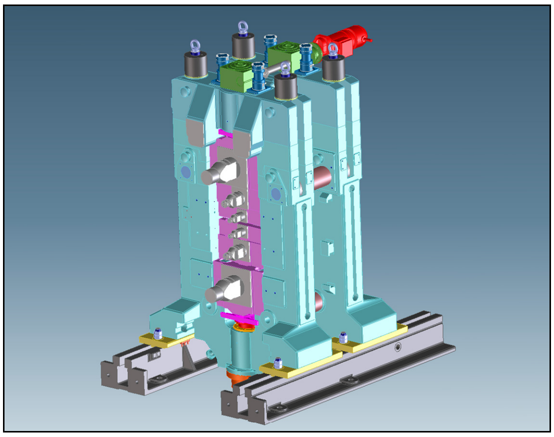

Fig. 4: Universal hot and cold rolling mill (Fa. MWE)

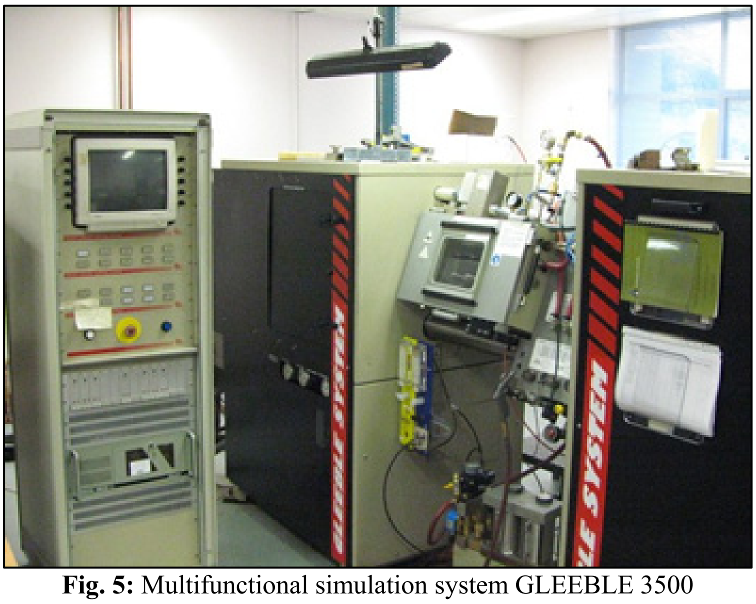

Fig. 5: Multifunctional simulation system GLEEBLE 3500

New software systems modeling and process simulation will enhance the possibilities of PDSS especially in the fields of modeling solubility characteristics in the state of thermo-dynamic equilibrium and phase transformation kinetics in disequilibrium states. The development of new software modules which offer possibilities for time-efficient simulations of forming processes is another key issue.

Research on material forming processes will be enhanced by a new metal forming laboratory which is equipped with a pilot rolling mill enabling the following process routes:

- hot rolling of flat material from the rolling heat with controlled intermediate and finishing cooling,
- cold rolling of flat products,
- section rolling with controlled intermediate and finishing cooling.

The rolling mill will have a roller barrel width of 600 mm and a diameters of 320/200mm. It will be equipped with a reversing drive. There will be a chamber furnace for heating up to 1400 °C and a binary cooling system (water, air) for cooling after rolling. For the heat treatment of cold rolled material there will be a furnace with a protective atmosphere (N_2 with up to 10% H_2).

Research Cooperation

Although, the development and installation of the new testing facilities has started already, it will take several years till all systems are available at PDSS. Therefore, to advance current research programs PDSS will work together with several partners who can cover the experimental testing which can not be performed at NITU MISIS. **Figure 6** illustrates the intertwined cooperation structure with the possible partners.

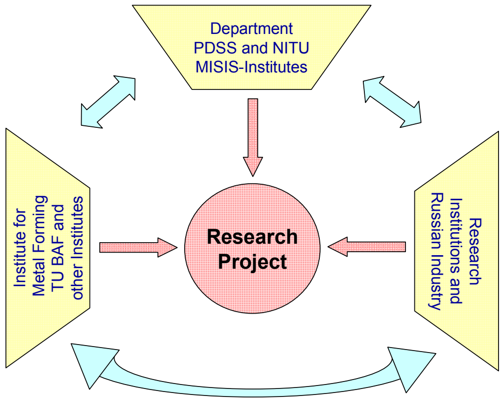

Fig. 6: Connection of department PDSS with partners

An especially close cooperation connects PDSS with the Institute for Metal Forming of TU Bergakademie Freiberg through which PDSS is able to use some unique testing and pilot facilities in Germany. Amongst others, these are.

- a multifunctional forming simulation system with analytical testing of phase transformation processes (**Figure 7**),
- a multifunctional GLEEBLE HDS-V40 simulation system with included testing of plan-strain forming from solidification heat, continuously casting and forming with very high deformation grades (**Figure 8**),
- a semi-continuous hot rolling mill for rolling strip and wire with controlled intermediate and finishing cooling (**Figure 9**). The reconstruction of strip-to-wire version is performed by employees of the institute,
- bar and wire drawing machines,
- facilities for sheet and bar testing in the temperature range between RT and 1000 °C.

All technical data for each facility are given in [6].

Fig. 7: Multidirectional deformation dilatometer

Fig. 8: **M**ultifunctional simulation system GLEEBLE HDS-V40

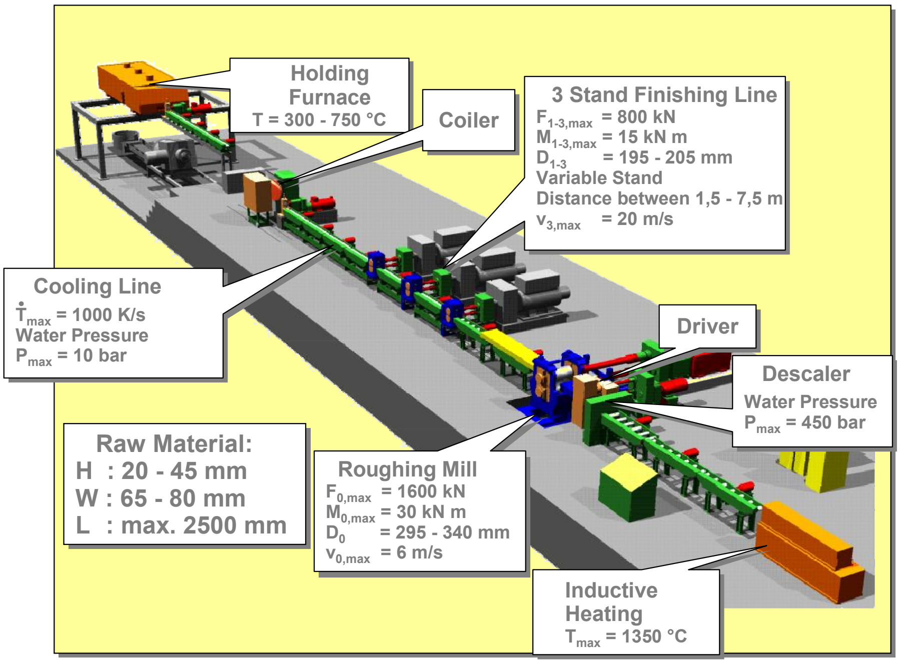

Fig. 9: Continuous pilot mill (flat products)

A special facility available at the Institute for Metal Forming is a pilot line for twin-roll casting and hot rolling of magnesium flat products. This offers possibilities for doing research on strip material from magnesium alloys with widths up to 700 mm (**Figure 10**). A detailed description of this facility is given by [7].

Fig. 10: Semi continuous pilot line for casting and rolling of magnesium strip

2. Scientific Approach and Examples for Future Development of Materials and Technologies

One of the most essential success factors for joint research projects is that all partners agree on a common approach for technological development. This part of the article describes some of these fundamental principles on the example of the hot rolling process (**figure 11**).

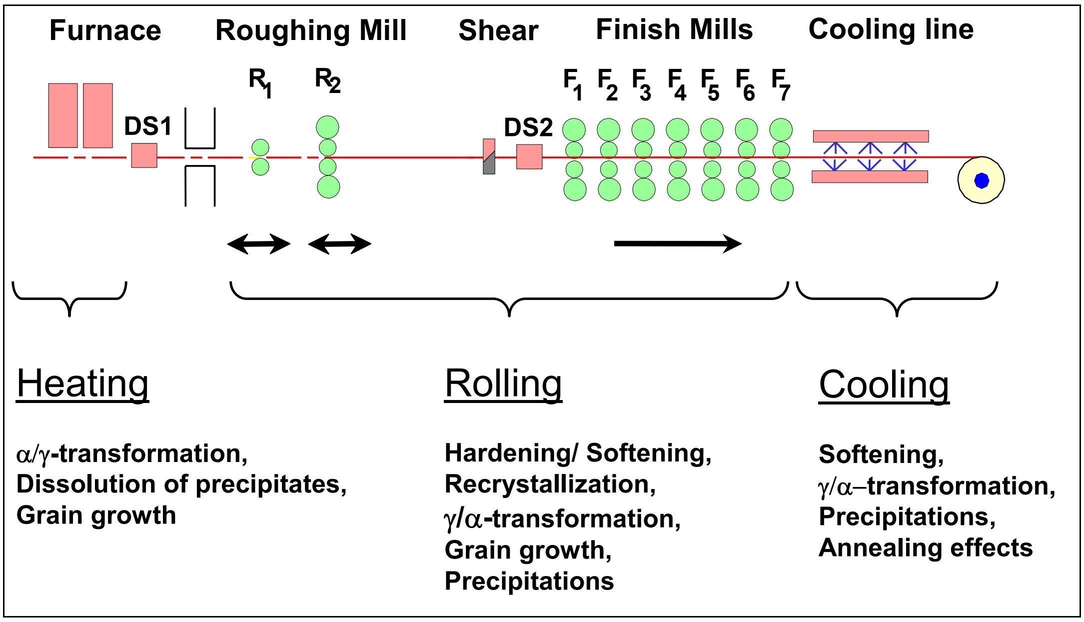

Fig. 11: Technology components e.g. of the hot strip production

Heating:
For the forming process and in respect to the properties of the finished product it is important to get sure that all alloying elements and micro-alloying elements go into solution. This is done by adjusting the heating process. The state of solution of all elements influences the forming behavior of the material as well as the precipitation hardening at lower temperatures.

The temperature which must be reached can be calculated for the thermodynamic equilibrium in which the interaction between the different elements is stable. An example for the procedure of these calculations is illustrated in **figure 12**. The diagram shows the amount of exsolution fraction in % on the y-axis and the temperature on the x-axis. In the example the micro-alloying element Niobium is fully dissolved only at temperatures above 1220°C. If the heating temperature is lower, there will be precipitation.

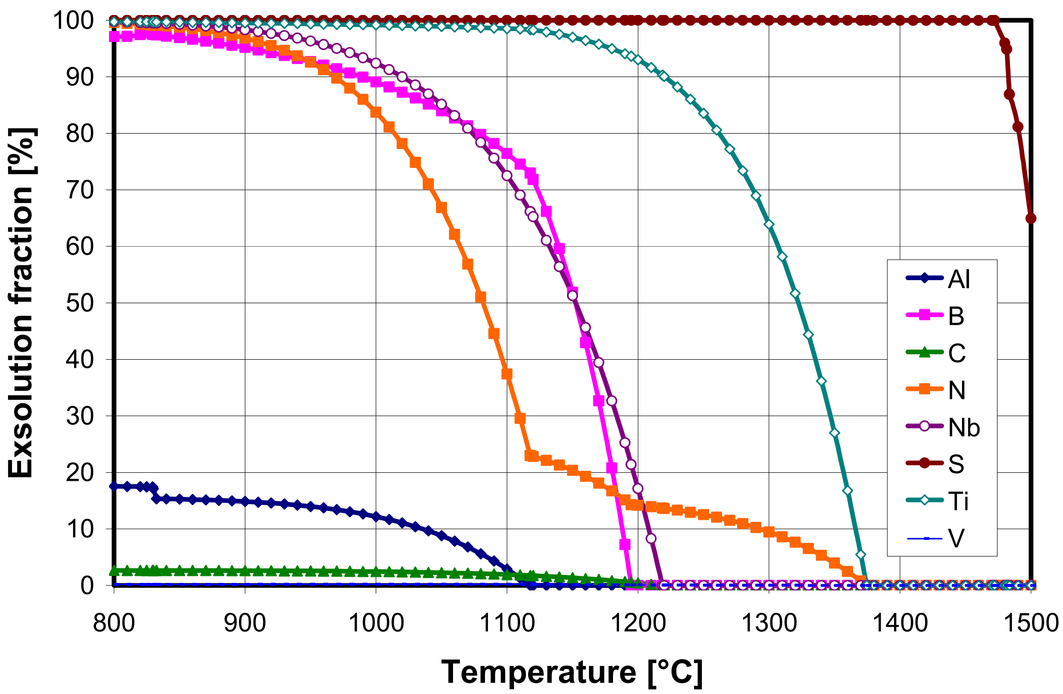

Fig. 12: Calculation of the dissolubility of selected alloying elements for steel S355

Hot rolling:
For the calculation of rolling schedules information about microstructure development and the energetic parameters are required. These can be derived from the flow curves for the relevant temperature range.

There are different approaches for calculating these flow curves. For fast calculations with simulation systems the semi-empiric models listed in **table 1** have proven to be effective.

Table 1: Mathematic models of dynamical and statical softening

Model of dynamical Recrystallization (DRX)	**Modell of statical Recrystallization** (SRX)
Zener-Hollomon-Dependence $Z = \dot{\varphi} \cdot e^{\frac{Q_W}{R \cdot T}} = A \cdot \left[sinh(\alpha \cdot \sigma_{max}) \right]^m$	Incubation time $t_0 = i_1 \cdot D_0^{i_2} \cdot \varphi^{i_3} \cdot \dot{\varphi}^{i_4} \cdot e^{\frac{Q_{t_0}}{R \cdot T}}$
Critical forming degree for DRX $\varphi_c = a_1 \cdot D_0^{a_2} \cdot \dot{\varphi}^{a_3} \cdot e^{\frac{Q_W}{R \cdot T}}$	Time for 50% statical recrystallization $t_{.5} = g_1 \cdot D_0^{g_2} \cdot \varphi^{g_3} \cdot \dot{\varphi}^{g_4} \cdot e^{\frac{Q_5}{R \cdot T}}$
Forming degree for 50% recrystallization $\varphi_{.5} = c_1 \cdot D_0^{c_2} \cdot \dot{\varphi}^{c_3} \cdot e^{\frac{c_4}{T}}$	Statical recrystallization fraction for $t \geq t_0$ $X_{stat} = \left(1 - X_{dyn}\right) \cdot \left[1 - e^{h_1 \cdot \left(\frac{t - t_0}{t_{.5} - t_0} \right)^{h2}} \right]; \; h_1 = -ln2$
Dynamical recrystallization fraction for $\varphi \geq \varphi_c$ $X_{dyn} = 1 - e^{-e_1 \cdot \left(\frac{\varphi - \varphi_c}{\varphi_{.5} - \varphi_c} \right)^{e2}}$	Statical recrystallization grain size $D_{stat} = s_0 + s_1 \cdot D_0^{s_2} \cdot \varphi^{s_3} \cdot \dot{\varphi}^{s_4} \cdot e^{\frac{Q_{stat}}{R \cdot T}}$
Dynamical recrystallization grain size $D_{dyn} = d_1 \cdot \dot{\varphi}^{d_2} \cdot e^{\frac{Q_W}{R \cdot T}}$	Grain growth $D_{KW} = \sqrt[n]{D_0^n + k \cdot t \cdot e^{-\frac{Q_{KW}}{R \cdot T}}}$

Examples for the dynamic softening which is visible from the flow curve are given in **figure 13**. It must be noted, that if the process does not start with the heating of the material but the forming directly succeeds the solidification the process runs differently and must be described by using different models [8]. As these kinds of production processes are very efficient they offer great economic potentials.

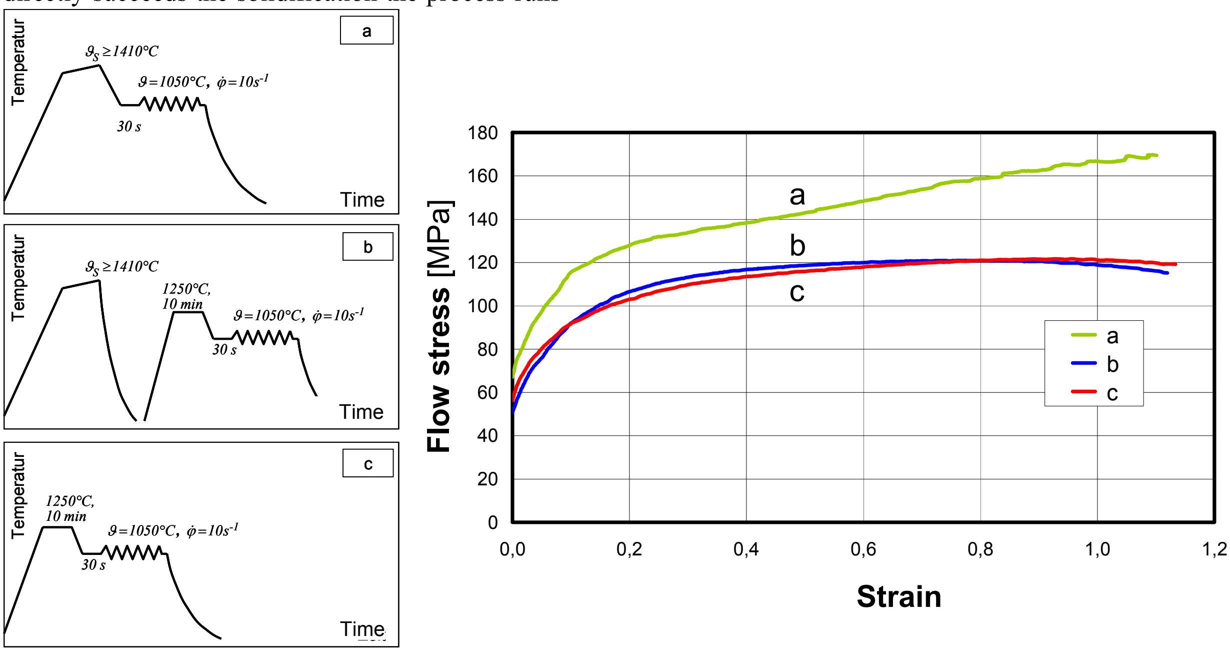

Fig. 13: Test conditions and determined flow curves for the direct rolling (a) and after the conventional reheating rolling (b, c) for steel S355

Figure 14 shows a special case there the effect of static softening is compensated by deformation induced precipitations at temperatures below 950 °C [9]. This explains the almost constant softening until a degree there the coarsening of precipitations increases and dislocation movement begins.

Mechanical Properties

The mechanical properties like for example yield and tensile strength can be calculated if the microstructure and the chemical composition are known. Respective formulas are published in the literature [12, 13].

3. Internationalization of the educational programs

Educational programs must be adapted to the requirements of the labor market. This applies to the content as well as to the exchange of students in international networks.

Students of metal forming at the NITU MISIS are provided with a broad and sound knowledge base on materials and forming processes. They are trained in all relevant competencies required for professional activity in the field of metal forming.

Today, due to the close cooperation which connects NITU MISIS with Czestochowa University of Technology and TU Bergakademie Freiberg studies of metal forming at the PDSS has an international focus. By visiting the partner universities, students get to know the different styles of studying and working as well as different educational and cultural systems. Therewith, they will be able to form a bridge between the cooperating nations.

The international double-degree programs have reached a pilot character and will be extended further. This should enable all students of metal forming to take part in one of the international programs of the three aforementioned universities. Promoting this development, industrial partners could help with financial support for these programs.

The importance of qualification measures for industry professionals has grown with the increase in competition and shortening innovation cycles for producing firms. While in the EU firms are often connected by industrial federations which help their partner companies to set up professional education programs, Russian companies regularly act isolated regarding qualification issues. Therefore, networks of research institutions and universities could take the role of establishing respective programs for professional further education in Russia. Another option which should be advanced as well is the adaptation of EU standards and the buildup of cooperative partnerships with educational networks from the EU.

In recent years, educational institutes from the EU more than once have tried to establish branches in Russia, but always failed because of economic reasons. Newly developed large educational firms can obviously not compete against the existing structures and networks of the established universities.

Katedra PDSS will offer professional training and further education courses to all metal forming and material processing companies in Russia. Different educational requirements and levels will be considered when setting up these programs. Therewith Katedra PDSS will contribute to the further successful development of Russia's metal processing industry and to raising the levels of process efficiency as well as enhanced quality of products.

4. Summary

Katedra PDSS is a progressive and innovative partner for basic and applied research in metal forming and materials processing. Students are provided with broad and sound knowledge in the fields of material sciences and forming processes as a prerequisite to develop enhanced technologies and materials for Russia's industry. Meeting future demands Katedra PDSS works together closely with international partners in research as well as in its educational programs.

Potential partners for Katedra PDSS are research institutes and companies in Russia, from the EU and from other parts of the world. Today, Czestochowa University of Technology and TU Bergakademie Freiberg are important partners, but also research institutes and industrial firms.

Main objectives of Katedra PDSS are to develop new energy-efficient materials and technologies. Therewith, the institute contributes towards the overall goal to save natural resources by applying innovative technologies. The approach of Katedra PDSS is to focus on the demanded characteristics and properties of the final product and to create materials meeting these functional demands.

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